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Vertical coupling of quantum islands in the CdSe/ZnSe submonolayer superlattices

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The usual laser structures are made in an agreement with the double heterostructure geometry [1]. In this case a waveguiding effect occurs due to larger refractive index in the central layer. To get an efficient waveguiding of the lightwave in this layer the difference between refractive indices of waveguiding region and cladding layers materials should be quite large and the thickness of the waveguiding region should be comparable with the wavelength of light. This means that these materials must be lattice matched and, generally, must have large bandgap difference, as it usually occurs that only large bandgap difference provides large difference between refractive index values. For thick active layers one is, thus, limited by the condition of lattice matching. This condition is valid for all compositions in the AlGaAs-GaAs case and for some fixed compositions for other III–V ternary systems. In many cases, however, this lattice matched heterocouple does not exist (e.g. diamond, Si, etc.) or, if exists, does not provide sufficient conductivity (ZnMgSSe:N [2], GaN:Mg [3]). At the same time one can offer principally new way to realize waveguiding by using a resonant refractive index enhancement due to exciton absorption in ultrathin insertions of narrow gap material in a wide gap matrix [4]. There is no necessity in lattice matching in this case as ultrathin insertions can be elastically strained and dislocation free. To provide sufficient thickness comparable to the lightwave in crystal one can stack these insertions.

The interaction between excitons and light causes sharp adsorption line. From the Kramers-Kronig equation which relate real and imaginary parts of the dielectric constant one can thus obtain the exciton-induced modulation of the refractive index. In the case of carrier injection when the gain arises at the lower energy side of the adsorption peak, the enhancement of the refractive index is more pronounced due to increased derivative of the gain-absorption curve [5]. In this case the refractive index enhancement appears in the spectral region shifted to the lower energy side as compared to the absorption maximum. Thus, for this wavelength, optical confinement is the most efficient and, e.g. in case of absorbing substrate, minor optical losses can be realized [6]. Thus, there is an energy window with small optical losses for the light propagated in the structure plane.

In the quantum well (QW) excitons exhibit free motion in the QW plane. In this case we should think about the exciton in-plane k-vector. Excitons with finite k-vector, as it was directly shown by Gross [7], cannot recombine radiatevly. At high temperatures and carriers densities, which are typical for lasing conditions exactly, the excitons with finite k-vector dominate. So it is necessary to get an additional particle for exciton scattering to accommodate its k-vector (for example LO-phonon). This many-body

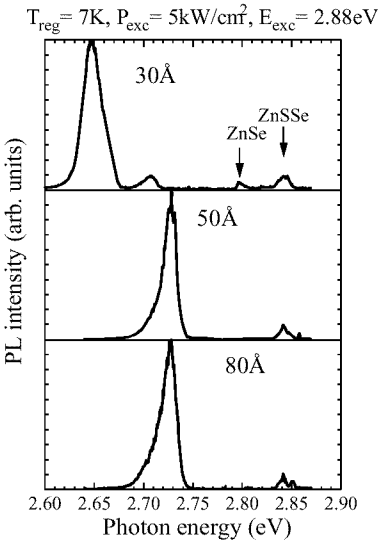

Fig. 1. PL of samples with different thickness of ZnSe spacer.

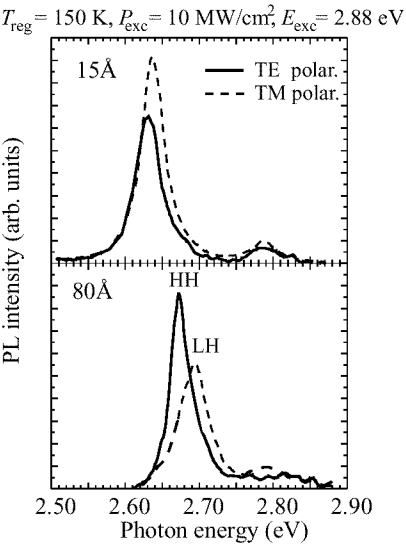

Fig. 2. Linear polarization dependence of edge emission for structures with 1.5 nm and 8 nm spacers.

scattering mechanism decreases material gain and shifts the gain maximum to the lower energy away from the excitonic waveguiding spectral window. To avoid this shift we proposed to use arrays of quantum dots (QDs) where excitons are effectively localized by QDs and the k-selection rules are broken [4]. Thus, to apply the concept of exciton induced waveguiding, described above, the sizes of quantum dots in all 3 dimensions should be comparable to the exciton radii. To fabricate these objects we proposed to use submonolayer (subML) CdSe depositions. SubML depositions result in dense arrays of uniform two-dimensional nanoscale islands [8]. In this paper, we discuss optical properties of subML CdSe/ZnSe superlattices (SL) with different spacers.

The structures extensively studied in this work were grown on n+ GaAs(100) substrates using a molecular beam epitaxy (MBE) [9]. All structures consist of 360 nm ZnSSe buffer and 60 nm ZnSSe cap layer lattice matched to the GaAs substrate. Between these layers there is a CdSe/ZnSe subML SL. CdSe insertion average thickness was estimated as 0.7 ML for all the structures. The ZnSe barriers have different thickness: 1.5 nm, 3 nm, 5 nm and 8 nm. The total thickness of SL is 60 nm for structures with 3 nm, 5 nm and 8 nm barriers and 30 nm for structures with 1.5 nm barriers. Consequently, the numbers of SL periods were different (20, 20, 12 and 8 consequently for 1.5 nm, 3 nm, 5 nm and 8 nm barriers).

Figure 1 shows PL spectra for structures with different spacers. The first remarkable result is that with decreasing in spacer thickness the PL drastically changes: a new peak at lower energy becomes dominant. This behavior can be explained by formation of vertically coupled QDs important for thin spacers, similar to shown for 3D InAs-GaAs QDs [10]. In this case the wavefunction of carriers in the neighbor islands are overlapped and the transition energy is lower. In this case the wavefunction of carriers in the neighbor islands are overlapped and the transition energy is lower. In the 8 nm and 5 nm cases there are only noncoupled QD emission, while the 3 nm

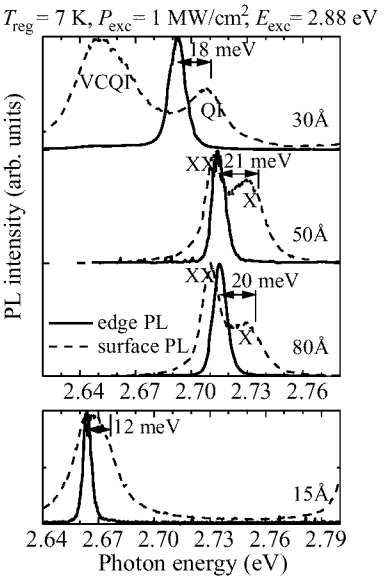

Fig. 3. Edge and surface PL of structures with different spacer thickness.

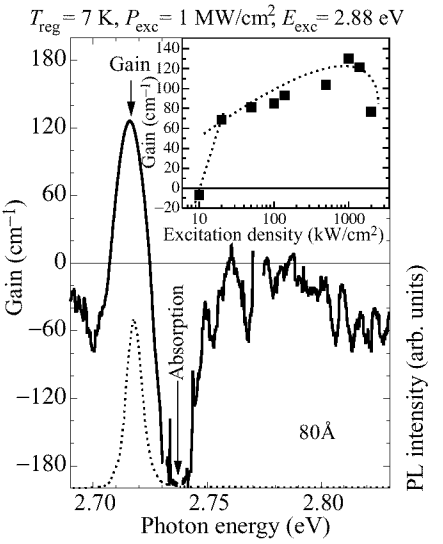

Fig. 4. Spectra of the gain (straight line) and stimulated emission (dotted line) of 8 nm spacer structure. Insert shows the excitation level dependence of the maximum gain value.

case shows emission from the both uncoupled and coupled states. Further decrease in spacer thickness resulted in increased intensity of coupled QDs and in full suppression of uncoupled QD luminescence.

The next possibility to prove the assumption about vertical correlation of QDs is to study polarized edge PL. As the height of the islands is only 1 or 2 MLs and lateral size is about 5 nm the symmetry of the hole wavefunction, which governs the polarization of edge emission is similar to the QW symmetry. In this case the light corresponding to HH exciton transition should be TE polarized and the light corresponding to LH exciton should have TM polarization. This behavior we can see for the 8 nm spacer structure (see Fig. 2). The lower energy TE polarized peak is corresponding to the HH exciton-induced ground state and the next — to the LH exciton-induced excited state. As opposite to this behavior for the 1.5 nm-spacer structure the situation is different. We have depolarized or weakly TM polarized emission. This tells us that the wavefunction symmetry is changed due to the vertical coupling of islands and the heavy hole wavefunction is more extended along the growth axis now.

Figure 3 shows PL from the surface at high excitation densities as well as the stimulated emission spectra measured in the edge geometry. You can see that the stimulated emission originates from uncoupled QDs except of the 1.5 nm-spacer case. In the 8 nm and 5 nm cases there are biexcitonic lines having a lower energy than the stimulated emission. This means that we have an excitonic nature of the stimulated emission. It is also confirmed by the energy positions of the stimulated emission and gain, which do not change with increasing in pump density. Thus many-carrier effects are not relevant in this case. In Fig. 3 the energy shift between the exciton ground state and the stimulated emission is also presented. For all the structures this shift is quite

smaller than the LO-phonon energy so there is a zero-phonon gain mechanism in the exciton waveguiding region.

In the Fig. 4 one can see the gain spectra well above the threshold obtained by variable stripe-length method. It is very important that even at densities two order of magnitude above the threshold there is still a region with strong excitonic absorption providing consequently an efficient exciton induced waveguiding. Without this waveguiding the positive gain can be hardly observed as internal optical losses in this structures with extremely thin buffer layers should be huge (more than 1000 cm^{-1}).

In the insertion to Fig. 4 the maximum value of gain versus excitation density is presented. One can see very fast onset of the gain near the threshold and then slow increasing which ends with gain saturation at very high excitation densities. This effect can be explained by the following: as stimulated emission can occur only in the narrow energy range due to exciton induced waveguiding not each QD can contribute to the gain. The number of QDs having proper transition energy is finite and after filling these QDs gain saturates. Further filling converts excitons to biexcitons and the gain in the exciton region decreases. At very high excitation levels when all the QDs are filled there is no excitonic absorption and, consequently, exciton induced waveguiding and this results in the vanishing of the gain.

In conclusions, in this paper we showed that decrease in the spacer layer thickness between subML sheets results in vertical correlation between QDs. Due to changing of the hole wavefunction symmetry edge PL of coupled QDs is weakly TM polarized while the emission of uncoupled dots is strongly TE polarized similar to QW case. Main absorption peak is not saturated when the gain peak develops at moderate excitation level while at very high excitation level saturation and suppression of the excitonic gain due to conversion of excitons to biexcitons and suppression of exciton induced waveguiding is observed.

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References

[1] Zh. I. Alferov and R. F. Kazarinov, Double Heterostructure Laser, Authors Certificate No. 27448, Application No. 950840 with a priority from March 30, 1963.
[2] H. Okuyama, Y. Kishita, T. Miyajuma, A. Ishibashi, K. Akimoto, *Appl. Phys. Lett.* **64** 904–906 (1994).
[3] B. Monemar, *Proc. the Second Int. Conf. on Nitride Semiconductors*, Tokushima (Japan), October 27-31, 1997.
[4] N. N. Ledentsov, et al., *Appl. Phys. Lett.* **69** 1343 (1996).
[5] I. L. Krestnikov, S. V. Ivanov, P. S. Kop'ev, N. N. Ledentsov, M. V. Maximov, A. V. Sakharov, S. V. Sorokin, C. M. Sotomayor Torres, D. Bimberg, Zh. I. Alferov, *J. Electron. Materials* **27** 72–75 (1998).
[6] I. L. Krestnikov, et al. *Phys. Stat. Sol.(b)* (to be published).
[7] E. Gross, S. Permogorov and A. Razbirin, *J. Phys. Chem. Solids* **27** 1647 (1966).
[8] M. Strassburg, et al. *Appl. Phys. Lett.* **72** 942–944 (1998).
[9] S. V. Ivanov, S. V. Sorokin, P. S. Kop'ev, J. R. Kim, H. D. Jung, H. S. Park, *J. Crystal Growth* **159** 1–4 (1996).
[10] A. F. Tsatsul'nikov, et al. *Semiconductors* **30** 953–958 (1996).